DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Navy Weather Research Facility

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
AREAS WITH EXTREME VERTICAL MOMENTUM SHEAR

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Synoptic patterns of extreme vertical momentum shear are investigated in relation to concentration of the 500-mb. temperature field.

5. AUTHOR(S) *(Last name, first name, initial)*
RIEHL, HERBERT

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
4 August 1967	19	4

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
NWRF 35-0867-131

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES
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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Naval Air Systems Command
Department of the Navy

13. ABSTRACT

Synoptic patterns of extreme shear of momentum along the vertical are investigated in relation to the concentration of the temperature field at 500 mb. For the United States, it was found in a study of two winters' data that all extreme momentum soundings were contained within an envelope in which the 500-mb. temperature gradient is at least 10° C./3.5° latitude. The probability of occurrence of these critical temperature gradient areas is 2 per cent. Approximately two thirds of such areas have extreme momentum profiles. The median fraction of the areas with critical temperature gradients that have extreme momentum shear is 0.4. Areas with high temperature gradients occurred mainly in the latitude of 40-45°.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Meteorology						
2. Momentum Profiles						
3. Missiles						
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NWRF 35-0867-131

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AREAS WITH EXTREME VERTICAL MOMENTUM SHEAR

NAVY WEATHER RESEARCH FACILITY
BUILDING R-48, NAVAL AIR STATION
NORFOLK, VIRGINIA 23511

AUGUST 1967

NAVY WEATHER RESEARCH FACILITY
BLDG. R-48, NAVAL AIR STATION
NORFOLK, VIRGINIA 23511

IN REPLY REFER TO:

NWRF/WHK: vl
5605
Ser: 109
8 March 1968

From: Officer in Charge, Navy Weather Research Facility
To: Distribution List

Subj: Meteorological Research Publication; forwarding of

Encl: (1) "Areas with Extreme Vertical Momentum Shear," NWRF 35-0867-131, Aug 1967

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FOREWORD

This publication was prepared under Navy Weather Research Facility Task 35, "Meteorological Techniques for Naval Missile and Satellite Operations," by Dr. Herbert Riehl, Professor of Atmospheric Science, Colorado State University. It describes a 500-mb. synoptic-chart technique for locating areas in which there is a high probability that severe vertical momentum profiles will occur.

Mr. Robert S. Haltiner, Task Leader of Task 35, coordinated the work at the Navy Weather Research Facility.

Reviewed and approved on 4 August 1967.

W. L. SOMERVELL, JR.
Captain, U. S. Navy
Officer in Charge
Navy Weather Research Facility

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1. INTRODUCTION

The vertical shear of horizontal air momentum is one of the primary factors that can produce difficulties for missile guidance systems. A previous report [4] described several parameters by which significant momentum shears could be characterized: thickness of layer with positive momentum shear; average slope of the momentum profile over this layer; and the existence of shallow layers with an extreme momentum increase within the whole thickness of positive shear under consideration. In that report, the frequency distribution of momentum profiles of possible concern to missile guidance systems was determined for a number of coastal and oceanic stations, and the probability of incidence of these extreme soundings was computed. In a coordinate system fixed with respect to the axis of the mean polar jet stream of winter [2], it was found that the probability of occurrence of these profiles in that season is near 2 per cent close to the axis and that it diminishes rapidly from there in both directions. A secondary maximum is suggested by some stations in the average subtropical jet-stream regions; however, not enough data were analyzed to describe the secondary maximum in detail.

This report discusses the results of a study into means for determining the existence of extreme vertical momentum profiles at locations where upper-air sounding stations are not available, and for predicting the occurrence of such profiles from conventional meteorological charts.

2. SYNOPTIC APPROACH

2.1 Objective of Investigation

It was apparent at an early date in the study, that a second approach to obtain the frequency distribution of severe momentum profiles could be chosen for comparison with the results derived from individual station statistics. Profiles with large momentum shear should not occur at random; rather, it should be possible to locate areas with such shear on synoptic charts. If these areas are determined over a sufficient time sample, the probability that a given area is occupied by large momentum shear can be computed; this probability can then be compared with that derived on a time-frequency basis from station records. Further, information could be obtained on the extent and shape of the areas with high momentum shear, on their position with respect to the major types of flow patterns within the waves in the westerlies, and on their propagation and persistence.

2.2 Method of Investigation

Except for parts of North America and Eurasia, the density of upper-wind observations is quite insufficient to permit direct delineation of the high-shear areas. Even there, as discussed below, sampling problems arise due to the restricted area covered by the phenomenon in many instances, and due to observational difficulties. Over the oceans, where a procedure of specification would be of primary value, an entirely different approach must be found.

Utilization of the geostrophic or gradient thermal wind relation suggests itself an obvious tool. The momentum is given by $M = \rho V$ where ρ is density of the air and V the vector wind velocity. In the situations under discussion, the turning of wind with height is generally small and may be neglected, so that we can determine $\partial M/\partial z$ assuming constant wind direction. The momentum of the geostrophic wind is

$$M = -\frac{1}{f}\frac{\partial p}{\partial n} \tag{1}$$

where f is the coriolis parameter, p is pressure and n is the coordinate perpendicular to M and taken positive to its left. Differentiating with respect to height (z) and introducing the hydrostatic relation $-\partial p/\partial z = \rho g$, where g is gravity:

$$f\frac{\partial M}{\partial z} = -\frac{\partial}{\partial n}\frac{\partial p}{\partial z} = g\frac{\partial \rho}{\partial n}$$

Using the equation of state for air $p = R\rho T$ (T-temperature, R-gas constant), we obtain:

$$\frac{Rf}{g}\frac{\partial M}{\partial z} = \frac{\partial}{\partial n}\left(\frac{p}{T}\right).$$

If constant pressure charts are utilized in synoptic work this becomes:

$$\left.\frac{Rf}{g}\frac{\partial M}{\partial z}\right)_p = -\frac{p}{T^2}\left.\frac{\partial T}{\partial n}\right)_p$$

or

$$\left.\frac{f}{g}\frac{1}{\rho}\frac{\partial M}{\partial z}\right)_p = -\frac{1}{T}\left.\frac{\partial T}{\partial n}\right)_p \tag{2}$$

the final form of the geostrophic thermal momentum equation. If gradient rather than geostrophic wind is considered, we can modify equation (2) by introducing

$$f' = f + 2kv \tag{3}$$

instead of f, where k is the curvature of an air trajectory in a natural coordinate system.

In equation (2) a good estimate of $-\partial T/\partial n$ for limiting values of $\partial M/\partial z$ can be obtained by suitable choice of constants. The coriolis parameter was taken as 10^{-4}/sec. for middle-latitude computations; p and T were taken from the standard atmosphere at the 500-mb. level. Then, for $\partial M/\partial z$ = 0.4 units/600 m., $\partial T/\partial n$ = -2.5° C./100 km. or -10° C./400 km., which is very nearly equal to -10° C./3.5° latitude.

The question now arises whether all momentum profiles with $\partial M/\partial z \geq 0.4$ units/600 m. can be found by locating the areas with $\partial T/\partial n \geq 0$° C./3.5° latitude at 500 mb., at least in middle latitudes in winter. The temperature gradient in jet-stream situations is known to be fairly independent of the vertical coordinate over the bulk of the mid-tropospheric layer [2] . Hence, there appears to be a reasonable chance that the proposed correlation might succeed. Accordingly, a statistical test was carried out over the United States where the greatest density of readily available wind observations exists. It is well recognized that bias on account of the mean circulation is introduced; however, there appeared to be no way to avoid such bias.

The periods October 1962 - March 1963 and October 1963 - March 1964, were chosen for study. Utilizing the insert 500-mb. charts at 0000 GMT appearing on the Daily Weather Map published by the U. S. Weather Bureau, each day was inspected and all areas with $\partial T/\partial n \geq 10°$ C./ 3.5° latitude were shaded. No allowance was made for the variation of the coriolis parameter over the United States. This map series has the advantage that only the broad features of the temperature field can be drawn, which is considered to be revelant. Some cases occurred where two isotherms at 5° C. intervals were very closely spaced for short distances of less than 300 n. mi. No extreme momentum profile was found in such situations. While this may be due to sampling problems, it was stipulated for computational purposes that the temperature difference considered must be 10° C. or more and that the long (downwind) axis of areas with critical temperature gradient must extend over at least 300 n. mi. (5° latitude).

2.3 Statistical Results

2.3.1 *500-mb. Temperature Fields*

In the 12-month sample, well over 100 days had areas with temperature gradients of 10° C. or more /3.5° latitude. Eliminating cases with very small areas, just discussed, 88 situations remained. Each area was measured with a fine grid of squares -- the whole United States contains 270 such squares. Table 2.1 gives the number of days having cases and the total area for each month, expressed as a fraction of the area of the United States; in table 2.2 both years are combined. It is seen that, with irregularities, the incidence of high-temperature gradient attains its maximum in middle and late winter as would be expected. On the average, the area with critical temperature gradients corresponded to nearly 2 per cent of the area of the United States. A breakdown by latitude is given in table 2.3. One can see that the distribution corresponds closely to that in figure 4.1 of Riehl [4] considering the mean jet-stream location over the United States.

2.3.2 *Temperature Gradients and Momentum Profiles*

For each of the 88 cases, all soundings were plotted within the region with critical temperature gradient and to some distance on the outside. Satisfactory comparison could not be established in 17 cases, so that the sample decreased to 71. Reasons were: (a) lack of soundings in small areas with critical temperature gradient, a sam-

TABLE 2.1. *Areas with Temperature Gradient of 10° C./3.5° Latitude, (by months)*

Month	Number of Days Having Cases	Total Area (as a fraction of area of U. S.)
1962		
October	7	.53
November	4	.26
December	10	1.17
1963		
January	15	.92
February	6	.63
March	8	.42
October	3	.18
November	1	.08
December	10	.97
1964		
January	8	.44
February	8	.36
March	8	.68

TABLE 2.2. *Areas with Temperature Gradient of 10° C./3.5° Latitude*

	Summary for Both Winters		Probability (per cent)
	Number of Days Having Cases	Total Area (as a fraction of area of U. S.)	
October	10	.71	1.2
November	5	.34	0.6
December	20	2.14	3.6
January	23	1.36	2.3
February	14	.99	1.8
March	16	1.10	1.8
Total	88	6.64	
Average			1.9

Table 2.3. *Distribution by Latitude of the Probability (per cent) of Occurrence of Critical Temperature Gradient.*

Latitude	Probability (per cent) of Occurrence of Critical Temperature Gradient
≥45	.73
49-44	3.65
35-39	1.88
<35	.74

pling problem; (b) cut-off at low levels of wind-sounding tabulations received from the National Weather Records Center, usually because of low-angle balloon observations; and (c) occasional highly erratic wind soundings with unrealistic variations from level to level, discussed previously by Riehl [1]. It may be added that every effort was made to utilize wind soundings cut off at 6 or 7 km. height in the data tabulation. Otherwise, the restriction on the sample of wind soundings would have been too severe. However, such utilization was not always possible and the shear above the cut-off level remained, of course, unknown.

The result was that no soundings with extreme momentum profiles [1] were encountered outside the areas with critical temperature gradient. Extreme profiles were found in 36 of the 71 areas. Where such profiles existed, they covered only a fraction of the area with large-temperature gradient. However, all indications are that a sampling problem exists which precludes further specification even in the United States. The areas with high-momentum shear often appear to have a narrow width, well below the average 200-mile spacing of upper-air stations. Under these conditions, only occasional evidence of the severe momentum profile bands is obtained. It is not possible to describe variations in type of extreme sounding with respect to the temperature field or 500-mb. flow pattern. We cannot specify, for instance, whether the extreme profiles are more likely to lie on one side of the maximum temperature concentration, or whether they are randomly distributed inside the 10°/3.5° latitude envelope. It is highly probable, that some of the 35 cases in which extreme profiles could not be found actually contained a narrow core of high-momentum shear.

2.3.3 *Fraction of Area with Extreme Profiles*

In view of the foregoing, it is very difficult to estimate the chance that a missile released within an area of critical temperature gradient may be lost because of control problems. As the best available alternative, the percentage was computed of soundings with extreme profiles out of all soundings within each envelope of critical temperature gradient. Lacking a better procedure, it will be assumed that these percentages hold also for the area relationship. The frequency distribution of table 2.4 was obtained:

[1] *As defined by Riehl [4].*

TABLE 2.4. *Frequency (per cent) of Occurrence of Various Percentages of the Area of Critical Temperature Gradient that is Covered by Several Momentum Profiles*

Per Cent of Area Covered by Extreme Momentum Profiles	Frequency (per cent)
<20	11
20-29	22
30-39	17
40-49	17
50-59	17
≥60	14

The mode of the distribution lies in the class interval 20 - 29 per cent; the median was 40 per cent, and is probably the best value for use in planning. It should not be overlooked, however, that on some occasions very high percentages of extreme momentum profiles occurred over the area of critical temperature gradient.

2.3.4 *Findings*

It has been shown that the areas with critical temperature gradient at 500 mb. occupy nearly 2 per cent of the area of the United States during the colder half of the year, October to March. Seasonally, the highest incidence is in the middle and late winter; latitudinally, the concentration occurs in the belt 40-45° N., just south of the climatic position of the polar jet stream.

Comparison of the areas with critical temperature gradient and observed momentum profiles showed that no extreme profiles were encountered well outside the zone with heavy isotherm concentration. However, the bias introducted by confining the study to the United States in winter is recognized. Inside the area with critical temperature gradient, extreme wind profiles were only found on half of the occasions (36 of 71). However, because of the shortcomings in the sampling procedure, it will now be assumed that two-thirds is a more representative value. With this assumption, the latitudinal distribution of probability of occurrence of extreme momentum shear may be computed. If we use the median value of .40 for the ratio of the area with high momentum shear to total area with critical temperature gradient, we then obtain table 2.5.

TABLE 2.5. *Probability (per cent) of Occurrence in Winter over the United States of an Extreme Momentum Profile at Various Latitudes*

Latitude	Probability (per cent) of Extreme Momentum Shear Over the United States
≥ 45	.20
40–44	1.00
35-40	.50
< 35	.20
Mean	~.5

When compared with figure 4.1 of the previous report [4], values are lower -- about one-half as large. The differences can partly be traced to the low incidence of cases in October and November, months not included in the earlier statistic. If these months are excluded, relatively good agreement between past and present computations is obtained.

It follows that if operations are suspended in areas with critical temperature gradient, missile failure due to momentum shear can be expected to be very rare under the circumstances here analyzed. If the decision is made to launch a missile which is sensitive to extreme momentum shears from inside a critical temperature area, the median risk is 40 per cent, and the occasional risk two-thirds, that control problems may be experienced. For the whole middle latitude belt from 30° to 50°, as far as represented by the United States, the overall risk is 0.5 per cent if operations are conducted randomly without taking the areas with strong temperature gradient into consideration.

3. SUPPLEMENTARY STUDIES

Several features observed during the study were explored further for their meteorological interest. A brief account follows.

3.1 Strength of Temperature Gradient

From the thermal momentum shear equation, the probability of extreme shear should increase with temperature concentration. At times the gradient has been as large as 15° and even 20° C./3.5° latitude. Nevertheless, no appreciable correlation was found. Further investigation of this result, which is possibly due to instrumental limitations in wind measurements and difficulties in drawing enough detail of the temperature field with existing data, is beyond the scope of this study.

3.2 Latitudinal Variation of Temperature Gradient

Because of the change of coriolis parameter with latitude, the critical temperature gradient should be larger in the north than in the south. Since the study was conducted without taking this variation into account, we may ask whether a higher percentage of cases contained extreme momentum profiles in the south than in the north. The result was negative; in each latitude belt the number of cases with and without extreme profiles was approximately equal. Again, an explanation cannot be offered. It should merely be pointed out that it would be very simple to allow for variation of the coriolis parameter, should later data indicate that this is desirable.

3.3 500-mb. Flow Pattern

Almost all the critical temperature gradient cases could be easily classified according to the 500-mb. flow into four groups: Northwest, Southwest, Trough and Westerly (fig. 3.1). The frequency distribution of these types, together with the number of cases with extreme momentum shear in each group, is given in table 3.1. Strong temperature gradients were most frequent in northwesterly currents importing cold domes from higher latitudes. Nevertheless, the per cent frequency of extreme momentum profiles was conspicuously low in such conditions, especially when compared with southwest flow. A possible explanation is suggested below, based on the curvature of the velocity field at 500 mb. No momentum shear maxima were found in occasional ridges, even though this type of flow was given particular attention because of the rare occurrence of ridges containing strong temperature gradients over the United States in winter.

3.4 Flow Curvature

Because the centripetal acceleration kV^2 (where k is the curvature of the trajectory of an air parcel and V is the wind speed) can attain large values in jet-stream zones, it was expected that a good correlation would be found between k and $\partial M/\partial z$ at a given value of $\partial T/\partial n$. The problems in determining k have often been discussed. Even the curvature of the projection of a path on the 500-mb. surface is difficult to compute in the highly baroclinic situations here considered.

TABLE 3.1. *Per Cent Frequency of Occurrence of Severe Momentum Profiles Under Various 500-mb. Flow Patterns*

Type	Number of Cases with Critical Temperature Gradient	Number with Extreme Momentum Shear	Per Cent Occurrence
NW	26	10	38
SW	21	14	67
Trough	9	6	67
Westerly	15	6	40
Total	71	36	51

Further, the motion is unlikely to be isobaric. Therefore, under these circumstances it is hard to determine k on a research basis, and practically impossible at present for operational purposes over the oceans.

The streamline curvature, k_s, or the contour curvature, k_c, will have the same sign as k in slowly moving waves in the westerlies, when wind speed is high. Assuming this relation to hold as a first approximation, we may try a statistical correlation between k_c as measured from the contours drawn on 500-mb. charts and the incidence of extreme momentum shear. For the 71 cases of strong temperature gradient, figure 3.2 displays the relationship between the radius of curvature r_c. (r_c is the reciprocal of k_c) and the incidence of extreme momentum shear. The extent of the area with critical temperature gradient has been used as a second parameter and is plotted on the vertical axis.

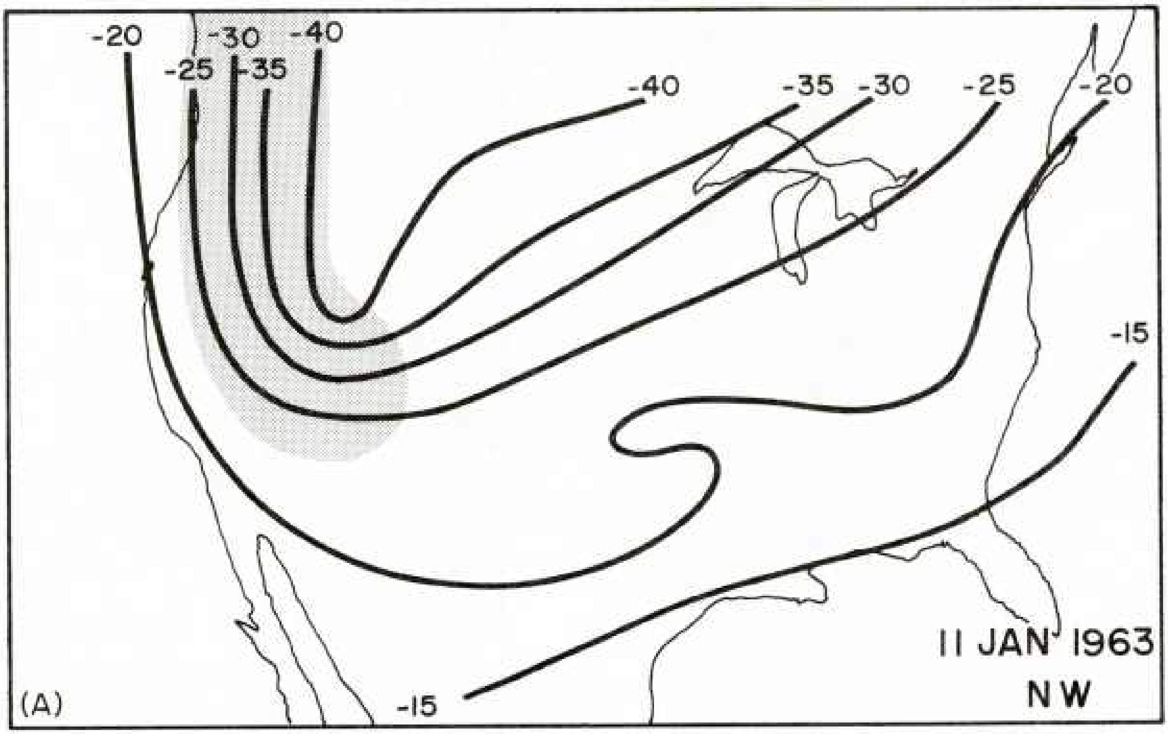
A strong correlation between k_c and occurrence of extreme momentum profiles is evident. For the cyclonic cases a curve is sketched which fairly well separates the occurrences and non-occurrences. During periods of straight or anticyclonic flow, mainly observed with southwest winds, virtually all cases contained extreme momentum profiles. These are plotted separately. At strong cyclonic curvature the probability of extreme shear is small, though not zero. The effect of size of area is slight by comparison, although there is a tendency for large areas to be associated with extreme profiles (possibly due to sampling alone).

The relationship in figure 3.2, although not of sufficient quality for operational use, nevertheless is strongly in the expected sense. It suggests a need to extend this study to other parts of the globe, where the general circulation has a mean ridge rather than a mean trough as over the eastern United States in winter.

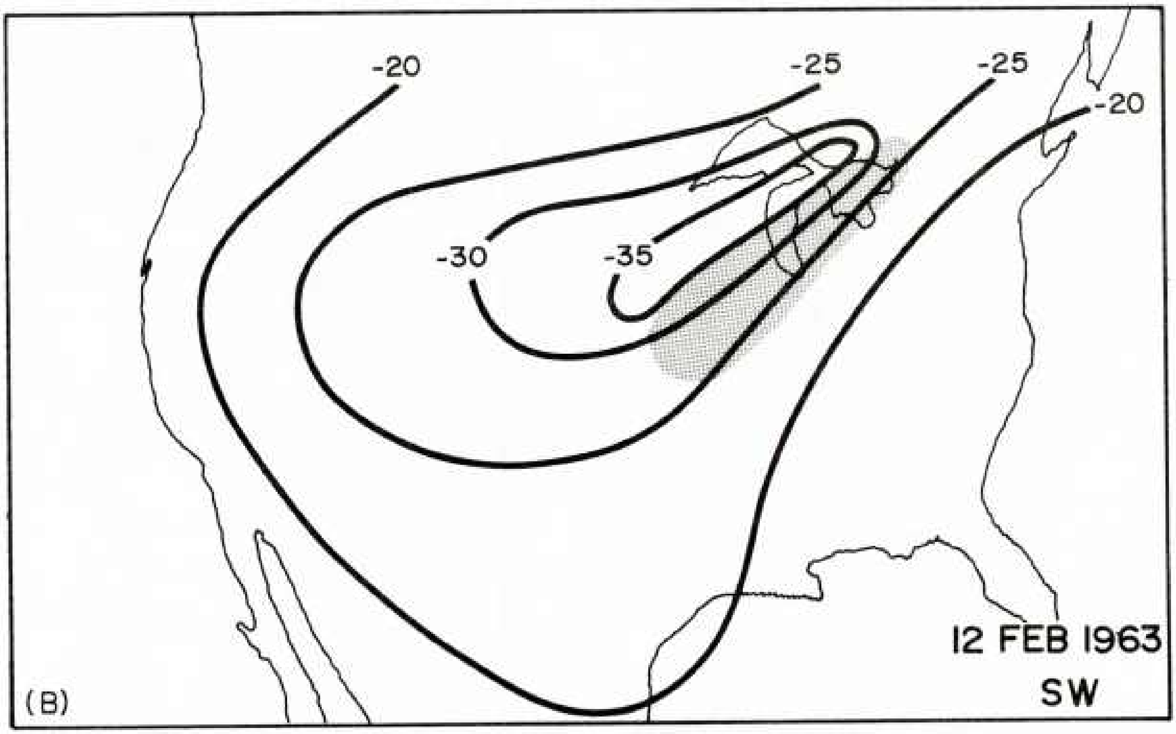
3.5 Examples

The isotherms at 500 mb. were concentrated in the midwest on 13 January 1963 (figs. 3.3 and 3.4), ahead of a trough which propagated to the eastern lakes region by the following day (figs. 3.5 and 3.6). Although the flow curvature remained weakly cyclonic, the envelope of critical temperature gradient contained an enlongated core of extreme momentum soundings. All computed soundings for 14 January 1963 are reproduced in figure 3.7. All of the most important soundings were terminated at relatively low elevations. In spite of strong winds to over 70 m./sec., stations such as Portland, Maine did not realize extreme momentum shear.

The strongest case during the period studied occurred on December 19-20, 1963, under west to west-northwest flow as described by Riehl [3] (figs. 13.11-13.13). At International Falls (fig. 3.8) the period with extreme momentum shear extended over two 6-hourly observations. As also observed in many other cases, the shear was only partly related to thermally stable layers, so that delination of frontal surfaces is not a reliable aid in locating momentum-shear zones. At New York (fig. 3.9) extreme shear was observed on three 6-hourly observations; here the relation between shearing zone and stable layer was much better than at International Falls. Comparing figures 3.8 and 3.9 we see that, in this case, the zone with strong momentum shear traveled eastward very rapidly.

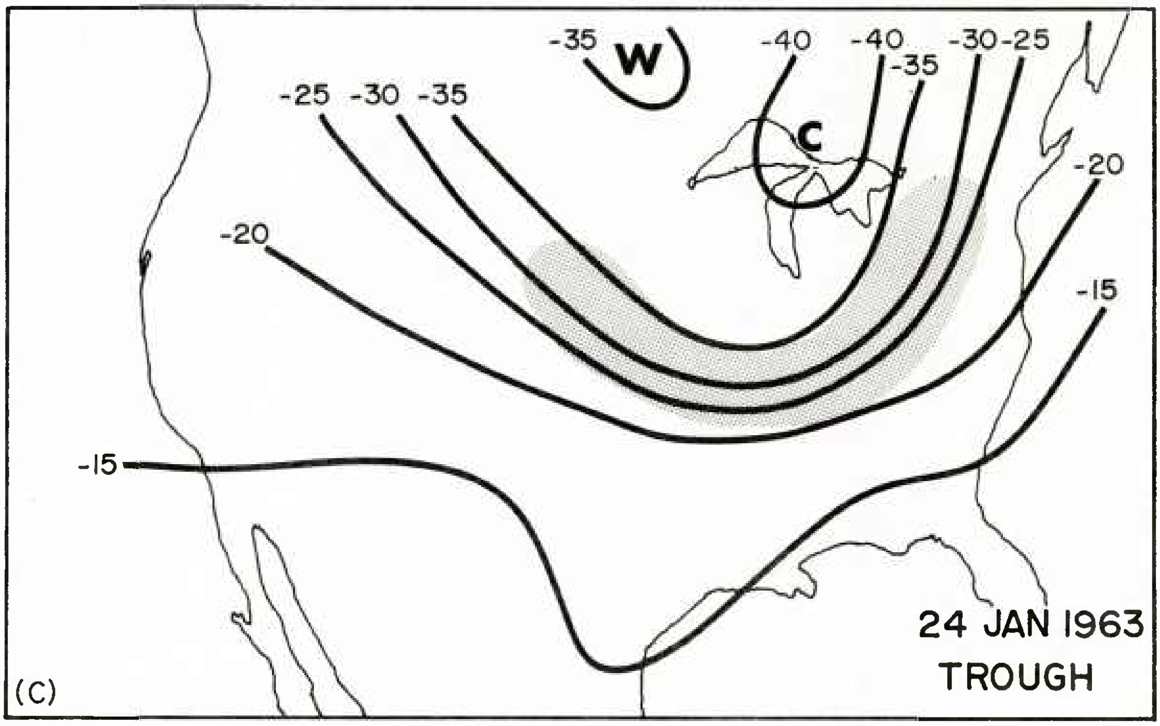


(a) Northwest

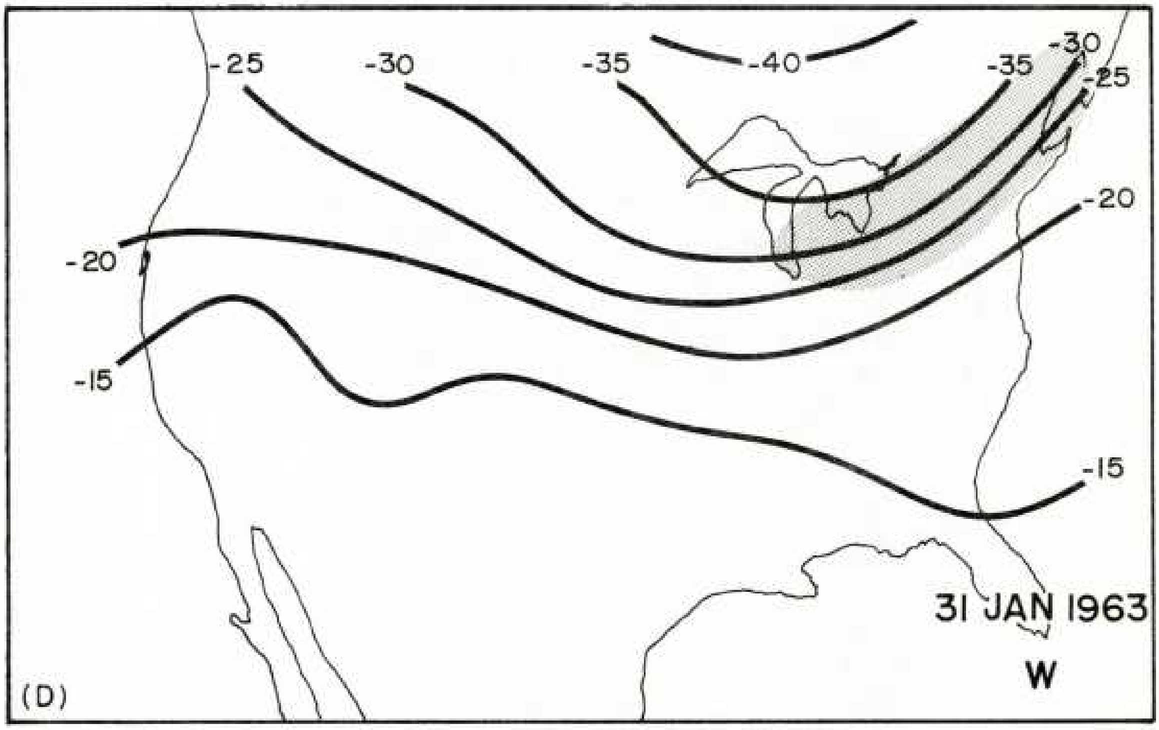


(b) Southwest

Figure 3.1. Examples of Isotherm Patterns with Critical Concentration.



(c) Trough



(d) Westerly

Figure 3.1. Examples of Isotherm Patterns with Critical Concentration.

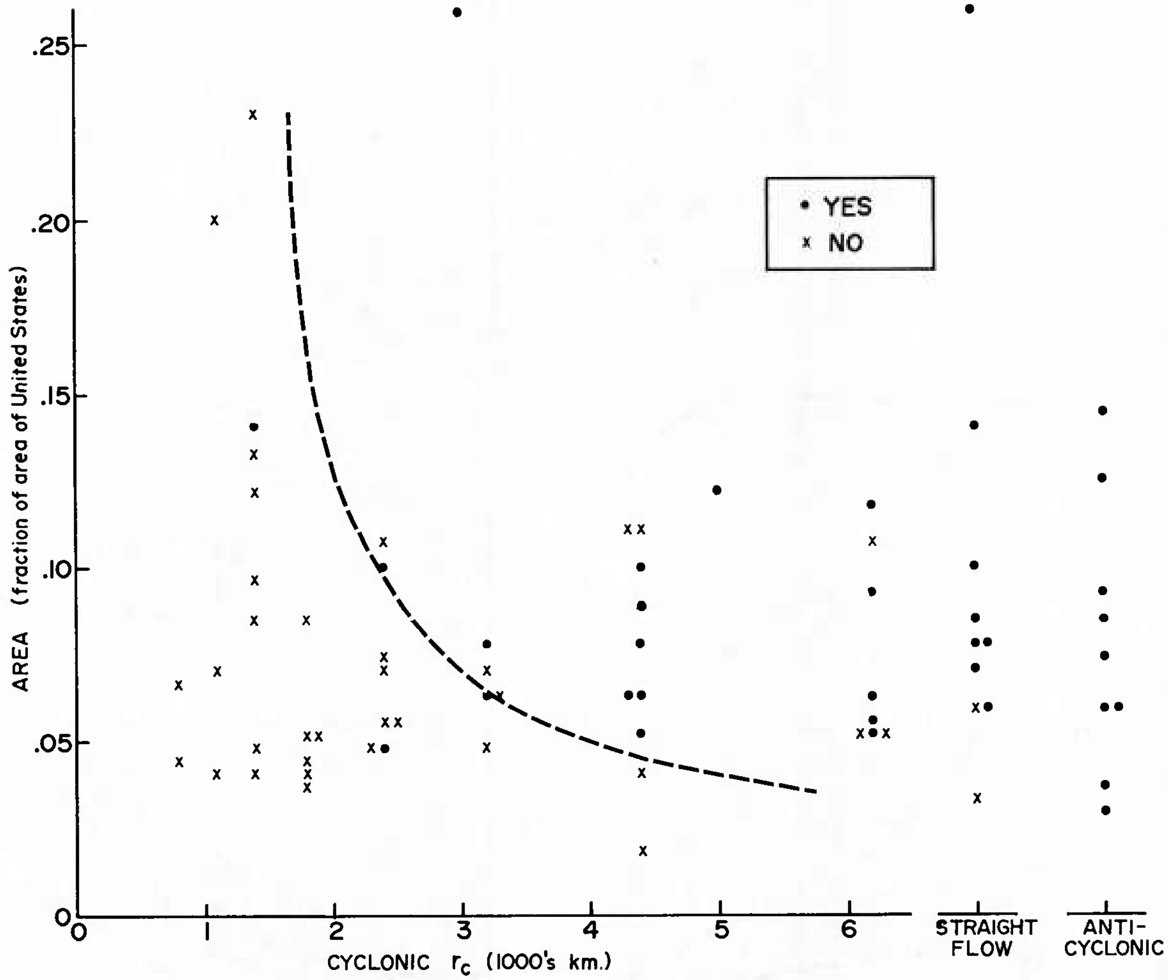


Figure 3.2. Correlation of Radius of Contour Curvature at 500 mb. (r_c) and Area with Critical Temperature Gradient with Occurrence or Non Occurrence of Extreme Momentum Profiles Within Area of Critical Temperature Concentration. A Dot Represents an Occurrence of Extreme Momentum Shear and an X is a Non-Occurrence.

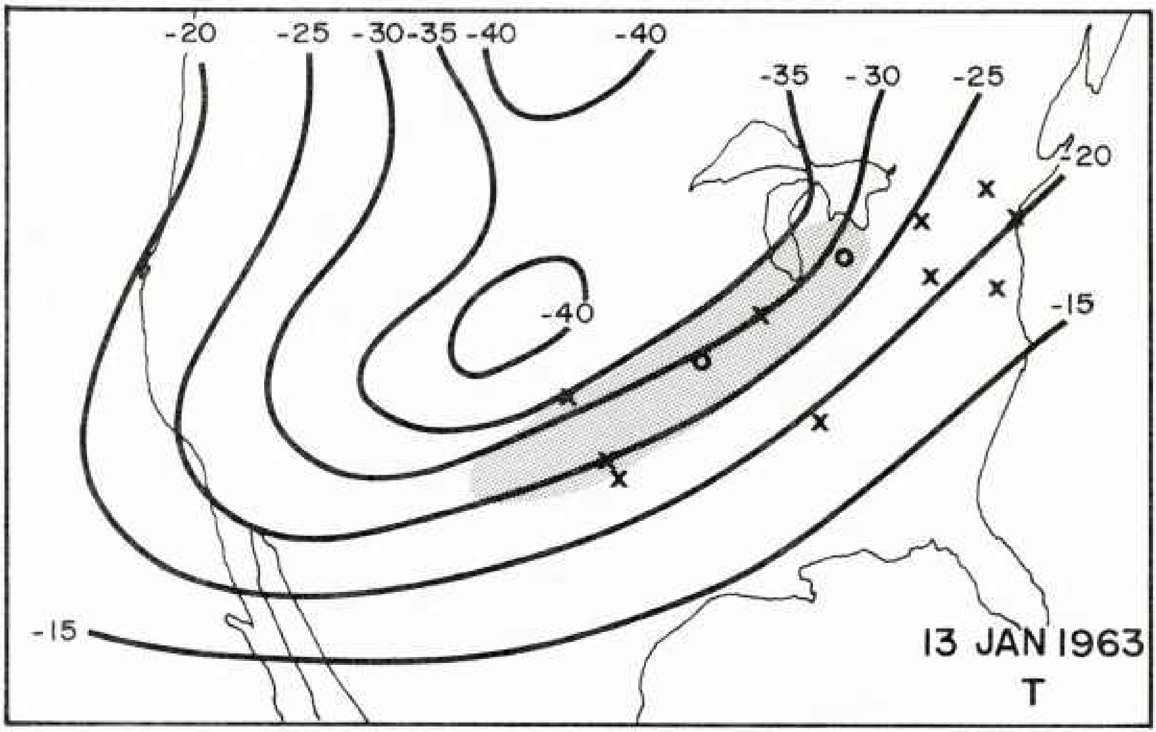


Figure 3.3. 500-mb. Isotherms (°C.) 13 January 1963, 0000 GMT. Area with Critical Temperature Gradient Shaded. Stations with Computed Momentum Soundings are Marked. Open Circles Denote Extreme Momentum Profile Observed; Crosses Denote Not-Observed.

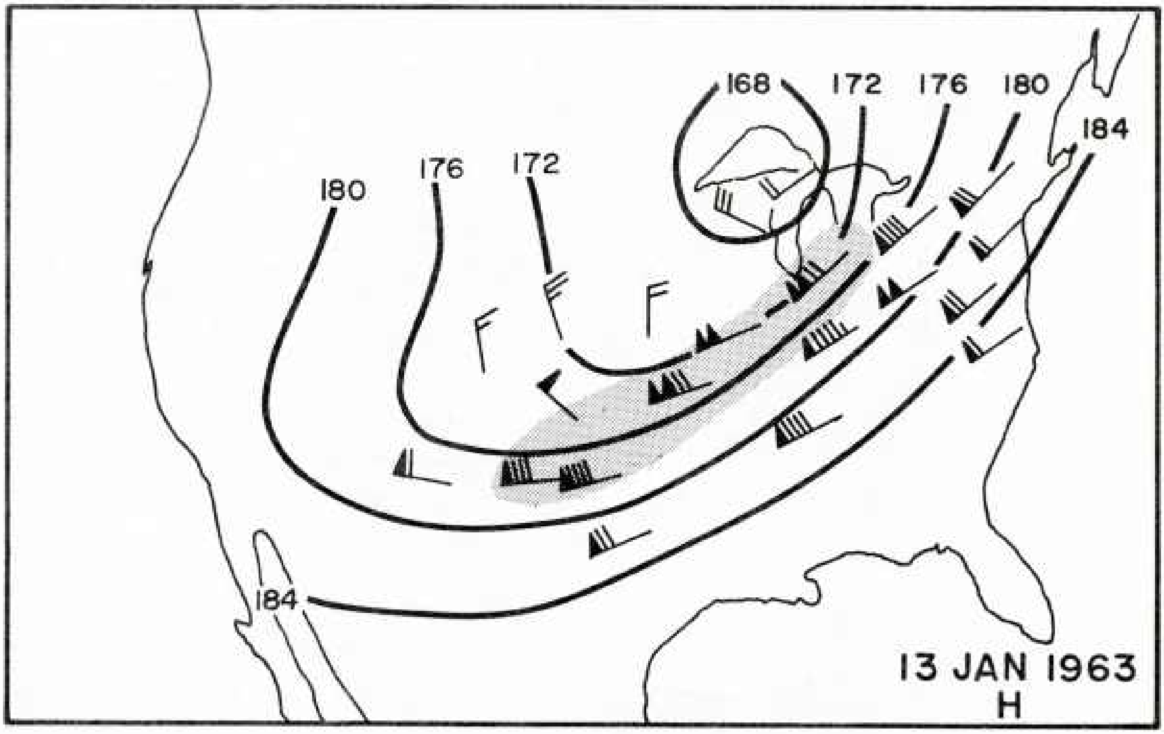


Figure 3.4. 500-mb. Contours (100's of feet) and Winds on 13 January 1963, 0000 GMT, In and Near Area with Critical Temperature Gradient.

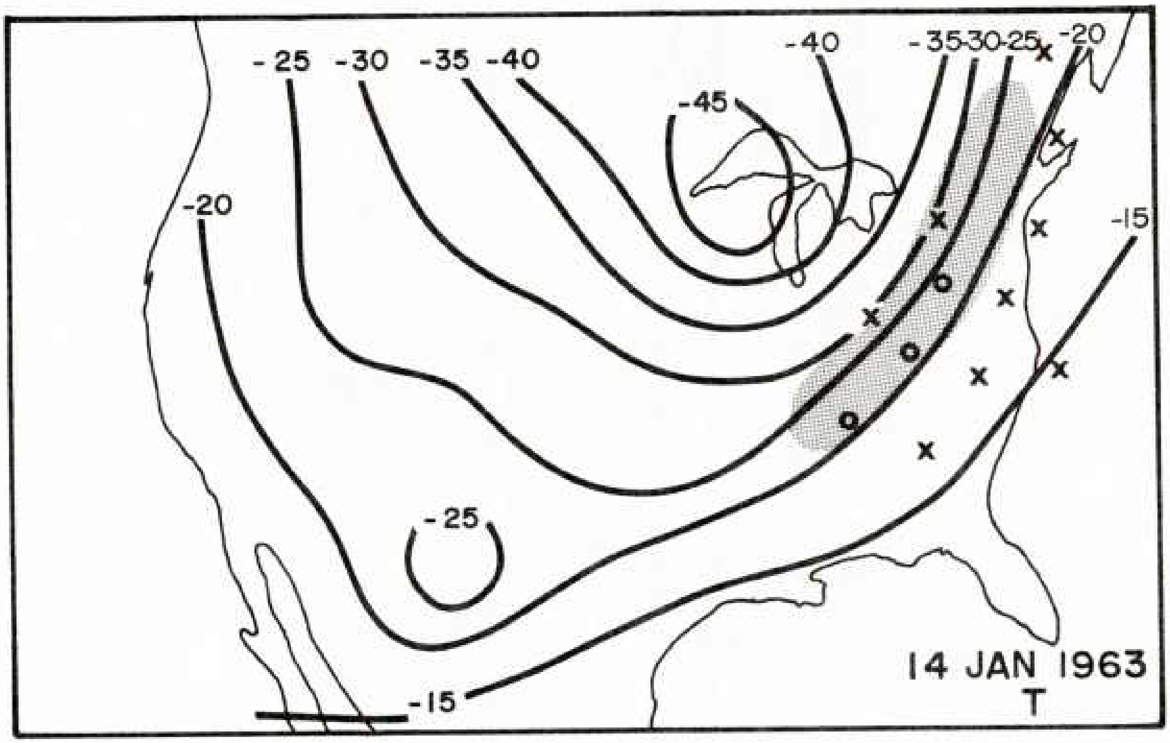


Figure 3.5. *500-mb. Isotherms (°C.) 14 January 1964, 0000 GMT. Area with Critical Temperature Gradient Shaded. A Second Small Area Near the Cold Core is Not Indicated. Stations with Computed Momentum Soundings are Marked. Open Circles Denote Extreme Momentum Profiles; Crosses Denote Not-Observed.*

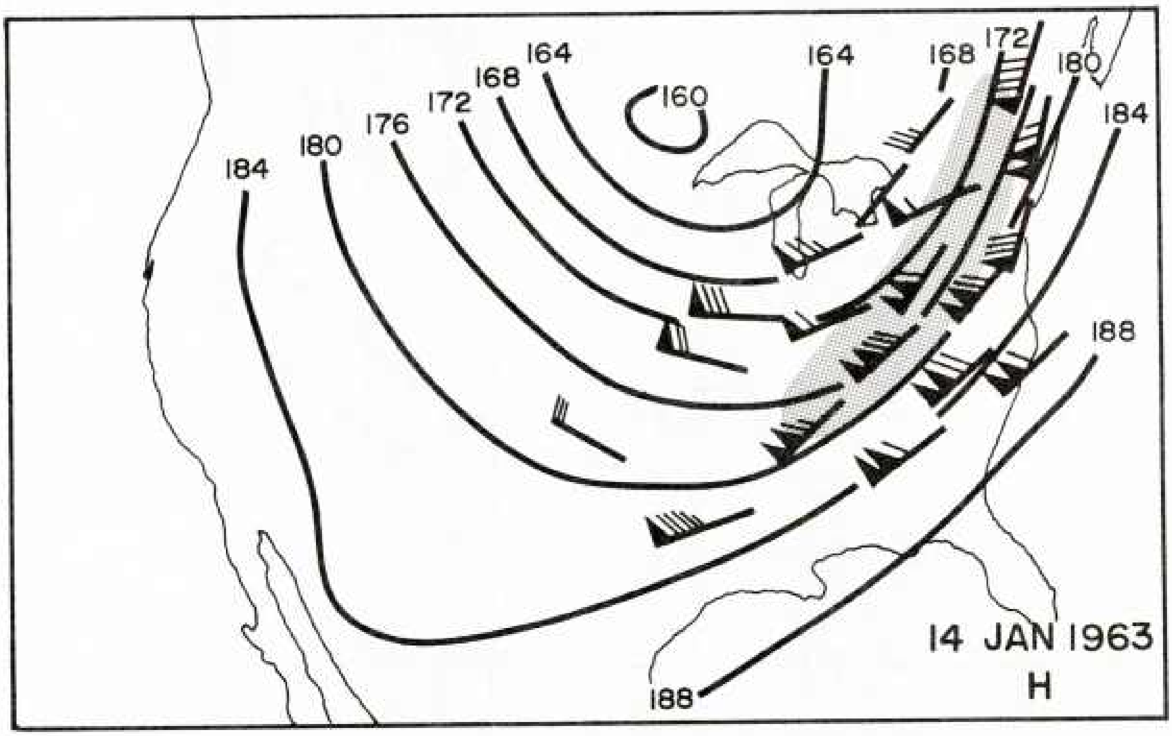


Figure 3.6. *500-mb. Contours (100's of feet) and Winds on 14 January 1963, 0000 GMT, In and Near Area with Critical Temperature Gradient.*

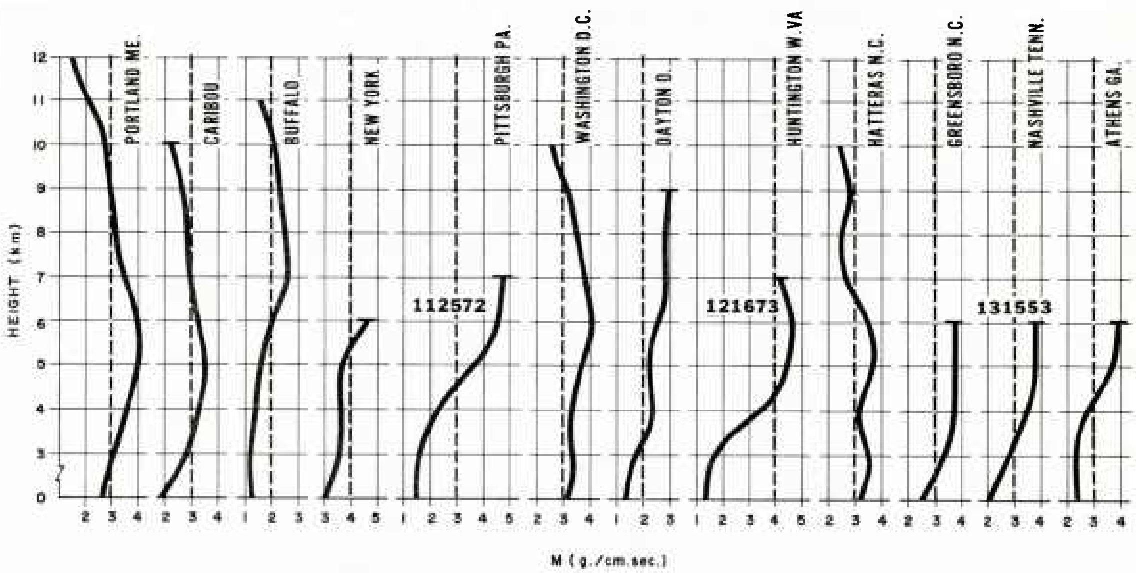


Figure 3.7. Vertical Plots of Momentum Profiles for Stations Marked in Figure 3.5. Bar at Top of Sounding Indicates Report Terminated. Extreme Profiles as Coded Following Riehl [4].

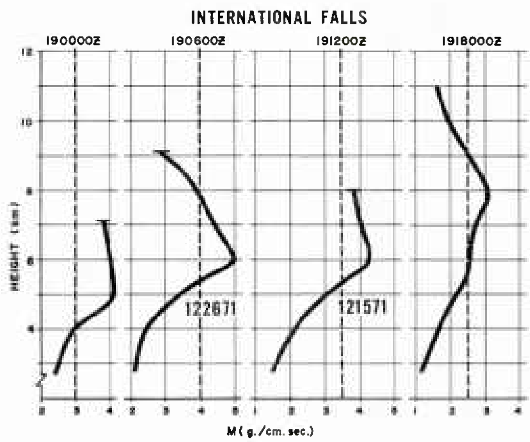


Figure 3.8. Vertical Plots of Momentum Profiles at International Falls on 19 December 1963. Codes Following Riehl [4].

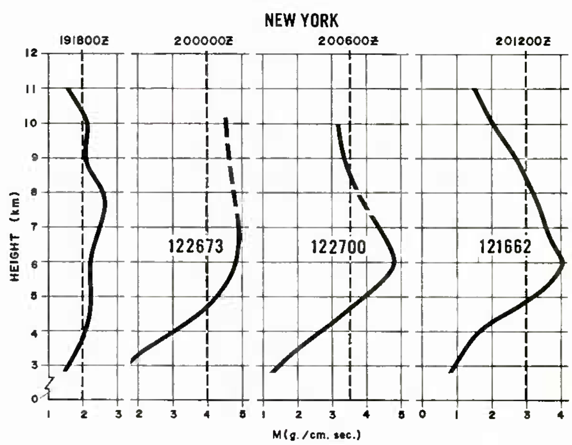


Figure 3.9. Vertical Plots of Momentum Profiles at New York Kennedy Airport, 19-20 December 1963. Profile for 0000 GMT 20 December Extrapolated Following Riehl [3]. Profile for 0600 GMT 20 December Interpolated in Layer of Strongly Oscillating Winds, as Reported.

4. CONCLUSION

This study has demonstrated, to the extent that conditions over the United States are representative of other regions, that over middle latitudes in winter the risk of missile-control problems due to momentum shear will be very small outside of zones where the 500-mb. temperature gradient is equal to or greater than 10° C./3.5° latitude. If operations are conducted in zones with critical temperature gradients, the average probability is 0.4 that extreme momentum profiles will be encountered; but the per cent area with such profiles is occasionally much larger. For operations conducted at random without regard to the 500-mb. temperature field, the overall probability is 0.005 (.5%) that a launch will occur in a zone of large momentum shear.

A principal limitation has been the need to restrict the study to the United States and its mean circulation, in order to realize the best possible approximation to a comparison between areas of strong 500-mb. temperature concentration and vertical momentum shear. Based on the present pilot findings, every effort should be made to extend these computations to other parts of the middle latitudes, especially over the oceans. It should also be noted that the subtropical jet stream has not been treated. At times, shallow wind maxima with very strong shear occur in the high troposphere, such as observed in the so-called "Vandenberg profile" or as measured at San Juan, Puerto Rico, on 1 April 1953 [2]. In these instances, the "root" of the momentum shear profile does not extend as low as 500 mb. and these cases must be the subject of another study.

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